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Palaeomagnetism and tectonic rotation of the Hastings Terrane, eastern Australia

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The Hastings Terrane comprises two or three major fragments of the arc-related Tamworth Belt of the southern New England Orogen, eastern Australia, and is now located in an apparently allochthonous position outboard of the subduction complex. A palaeomagnetic investigation of many rock units has been undertaken to shed light on this anomalous location and orientation of this terrane. Although many of the units have been overprinted, pre-deformational magnetizations have been isolated in red beds of the Late Carboniferous Kullatine Formation from the northern part of the terrane. After restoring these directions to their palaeohorizontal (pre-plunging and pre-folding) orientations they appear to have been rotated 130° clockwise (or 230° anti-clockwise) when compared with coeval magnetizations from regions to the west of the Hastings Terrane. Although these data are insensitive to translational displacements, a clockwise rotation is incompatible with models previously proposed on geological grounds. While an anti-clockwise rotation is in the same sense as these models the magnitude appears to be too great by about 100°. Nevertheless, the palaeomagnetically determined rotation brings the palaeoslopes of the Tamworth Belt, facing east, and the Northern Hastings Terrane, facing west before rotation and facing southeast after rotation, into better agreement. A pole position of 14.4°N, 155.6°E ($A_{95} = 6.9°$) has been determined for the Kullatine Formation (after plunge and bedding correction but not corrected for the hypothetical rotation). Reversed magnetizations interpreted to have formed during original cooling are present in the Werrikimbe Volcanics. The pole position from the Werrikimbe Volcanics is at 31.6°S, 185.3°E ($A_{95} = 26.6°$). These rocks are the volcanic expression of widespread igneous activity during the Late Triassic (~ 226 Ma). While this activity is an obvious potential cause of the magnetic overprinting found in the older units, the magnetic directions from the volcanics and the overprints are not coincident. However, because only a few units could be sampled, the error in the mean direction from the volcanics makes it difficult to make a fair comparison with the directions of overprinted units. The overprint poles determined from normal polarity magnetizations of the Kullatine Formation is at 61.0°S, 155.6°E ($A_{95} = 6.9°$) and a basalt from Ellenborough is at 50.7°S, 148.8°E ($A_{95} = 15.4°$), and from reversed polarity magnetizations, also from the basalt at Ellenborough is at 49.4°S, 146.2°E ($A_{95} = 20.4°$). These are closer to either an Early Permian or a mid-Cretaceous position, rather than a Late Triassic position, on the Australian apparent polar wandering path. Therefore, despite their mixed polarity, and global observations that the Permian and mid-Cretaceous geomagnetic fields were of constant polarities, the age of these overprint magnetizations appears to be either Early Permian or mid-Cretaceous.

Key words: Hastings Terrane, palaeomagnetism, southern New England Orogen, tectonic rotation.

INTRODUCTION

The anomalous position of the Hastings Terrane (Scheibner 1985) on the eastern (outboard) margin of the southern New England Orogen has been explained by models including: (i) an allochthonous origin (Leitch 1980; Lennox & Roberts 1988); (ii) transcurrent motion from a position southeast of the present eastern termination of the Tamworth Belt (Cawood 1982) between Newcastle and Taree; and (iii) oroclinal bending of the southern part of the orogen (Korsch & Harrington 1987). Palaeomagnetism offers the possibility to test, or at least constrain these models, though the widepread magnetic overprinting that has frustrated earlier studies on the Hastings Terrane (Idnurm & Scheibner 1974) and the New England Orogen (Klootwijk 1985) may prevent a conclusive result. To counter this problem an extensive sampling programme was undertaken to determine those units whose remanence may have survived overprinting. The ultimate goal of this study is the construction of an apparent polar wander path for the Hastings Terrane for comparison with the Devonian to Jurassic apparent polar wandering path from the Australian craton and other parts of the New England Orogen.

GEOLOGY

The Hastings Terrane comprises two or possibly three major fragments (Figure 1a), each of which is characterized by a particular stratigraphy and structural style. The Northern Hastings Terrane contains a succession of Early to Late Carboniferous sediments of predominantly marine origin; the Southern Hastings

Terrane is a Middle Devonian to Late Carboniferous sequence which changes from entirely marine to paralic at the top (Roberts *et al.* 1993a); and the Port Macquarie Terrane, a serpentinite mélange with blue-schist slices, some of which were dated as Ordovician, Silurian to Late Devonian chert, slate, volcanogenic sediments, slates attributed a Permian age and intrusive metadolerite and serpentinite (Leitch 1980). The boundaries between the Port Macquarie Terrane and Southern Hastings Terrane are faults, commonly containing serpentinite. Faults also separate eastern and western parts of the Southern Hastings Terrane and Northern Hastings Terrane, although in the east this boundary has been complicated by post-emplacement faulting. In the central part of the Hastings Terrane the boundary is obscured by younger volcanics and granitoids with extensive contact aureoles (Roberts *et al.* 1993a; Figure 1). Although the distribution and nature of Permian successor basin sediments suggest that the Northern Hastings Terrane and Southern Hastings Terrane were juxtaposed prior to the Early Permian, the different structural histories of each terrane suggest that there was also later movement between these parts of the Hastings Terrane.

The sedimentary successions in the Northern Hastings Terrane and Southern Hastings Terrane accumulated in close proximity to a volcanic arc within the precursor of the southern New England Orogen. Previous workers (e.g. Day *et al.* 1978; Roberts & Engel 1980), termed this region the Tamworth trough or Tamworth shelf and, together with Leitch (1974), interpreted it as a region of deposition extending from a volcanic arc in the west to deeper water in the east during the Devonian and Carboniferous. Application of the terrane concept to the southern New England Orogen by Aitchison *et al.* (1992) has led to the Devonian succession to the top of the Baldwin Formation (Frasnian) being referred to the Gamilaroi Terrane and interpreted as having been formed in intra-oceanic arc and arc–rift settings, east of an easterly dipping subduction zone. The succeeding Famennian to Carboniferous sediments of the Tamworth Belt are overlap sequences which accumulated in the fore-arc region. The Anaiwan Terrane to the east is an accretionary complex developed at a westerly dipping subduction zone, the direction of subduction having flipped and been relocated because of collision of the oceanic arc with the Lachlan Orogen at the eastern edge of Gondwana in the latest Devonian (Aitchison *et al.* 1992). As outlined below, lower parts of the succession within the Southern Hastings Terrane could well have accumulated adjacent to an oceanic arc, but, as with all except a limited region around Keepit Dam on the western margin of the Tamworth Belt, where there is a disconformity, there is no structural or stratigraphic evidence in New South Wales supporting a collision with the Australian craton during the Late Devonian. Famennian to late Visean rocks in the Southern Hastings Terrane and Early Carboniferous rocks in the Northern Hastings Terrane may represent

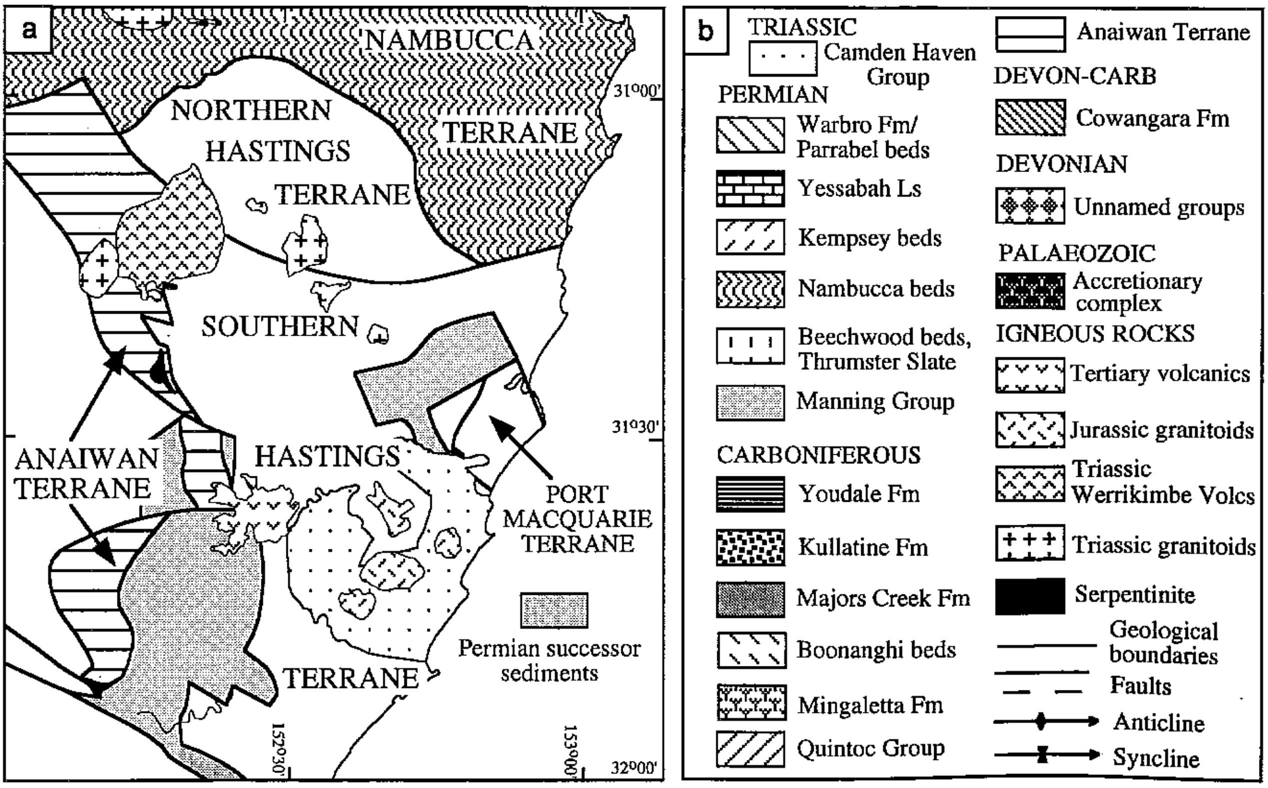

Figure 1 Hastings Terrane, southern New England Orogen. (a) Geological sketch map indicating parts of the Hastings Terrane and adjacent terranes; (b) legend; and (c) geological map of the Hastings Terrane (from Roberts *et al.* 1993a) showing sampling sites. 1: Basalt at Ellenborough (Elb1–6); 2: Kullatine Formation (Kul5, 6); 3: Kullatine Formation (Kul2, 7); 4: Kullatine Formation (Kul1, 3, 4); 5: Werrikimbe Volcanics (Wer1); 6: Werrikimbe Volcanics (Wer2–6).

deep-water environments within a fore-arc basin fed by an andesitic to basaltic source, whereas most latest Visean to Namurian sediments indicate shallowing of the basin and closer proximity to an ignimbritic source.

Stratigraphy

The succession within the Northern Hastings Terrane (Figure 2) commences with ?Early Carboniferous turbiditic siltstone, fine-grained lithic sandstone and conglomerate (Boonanghi beds) conformably overlain by a shallowing-upwards sequence of coarser lithic sandstone, minor siltstone and conglomerate, with rare tuff and carbonaceous shale at the top (Majors Creek Formation). Sediments within the Majors Creek Formation are finer grained in the western Northern Hastings Terrane, and non-marine rocks are confined to the northeastern Northern Hastings Terrane, indicating that depositional environments deepened westwards. The

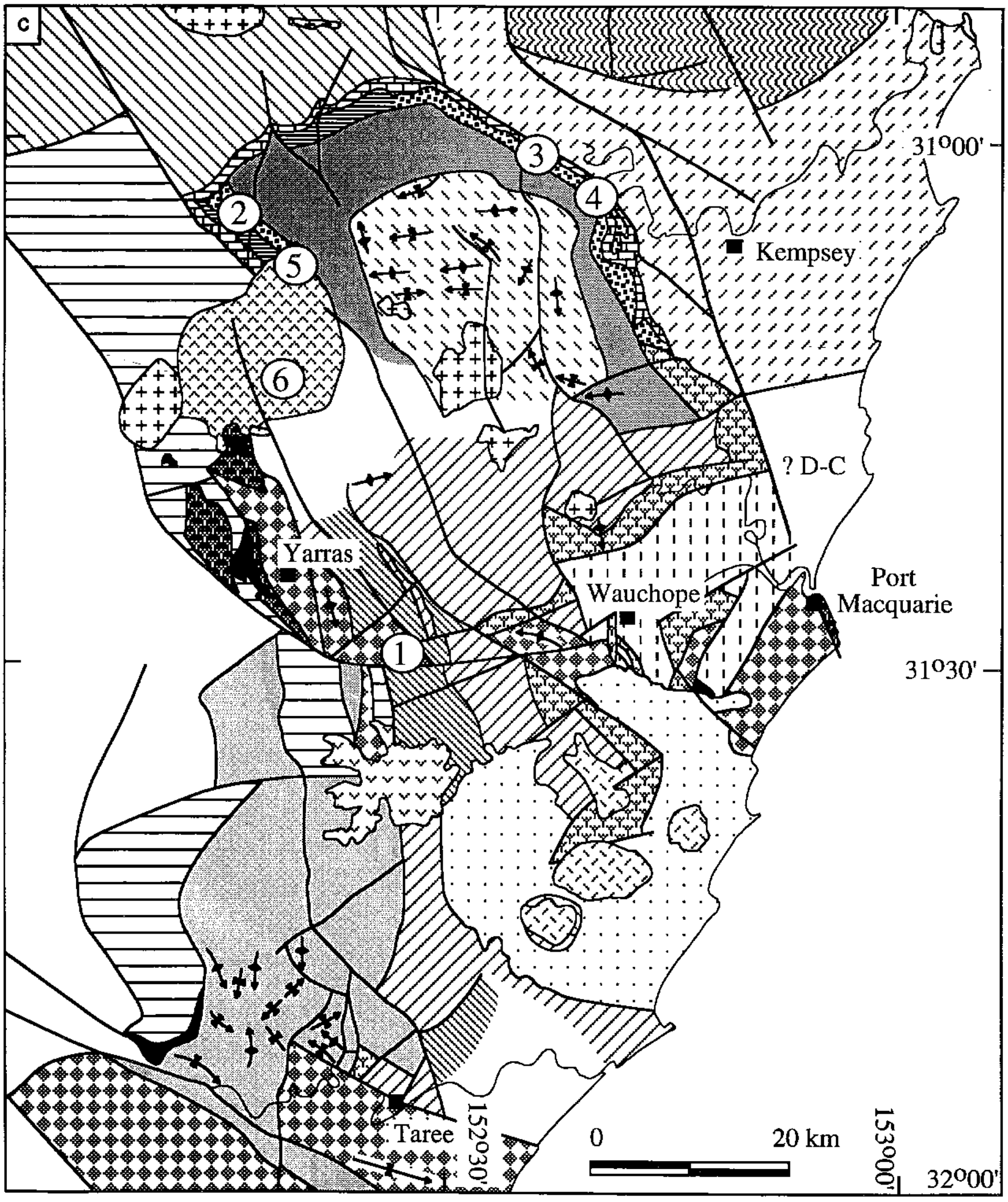

Figure 1 (Continued).

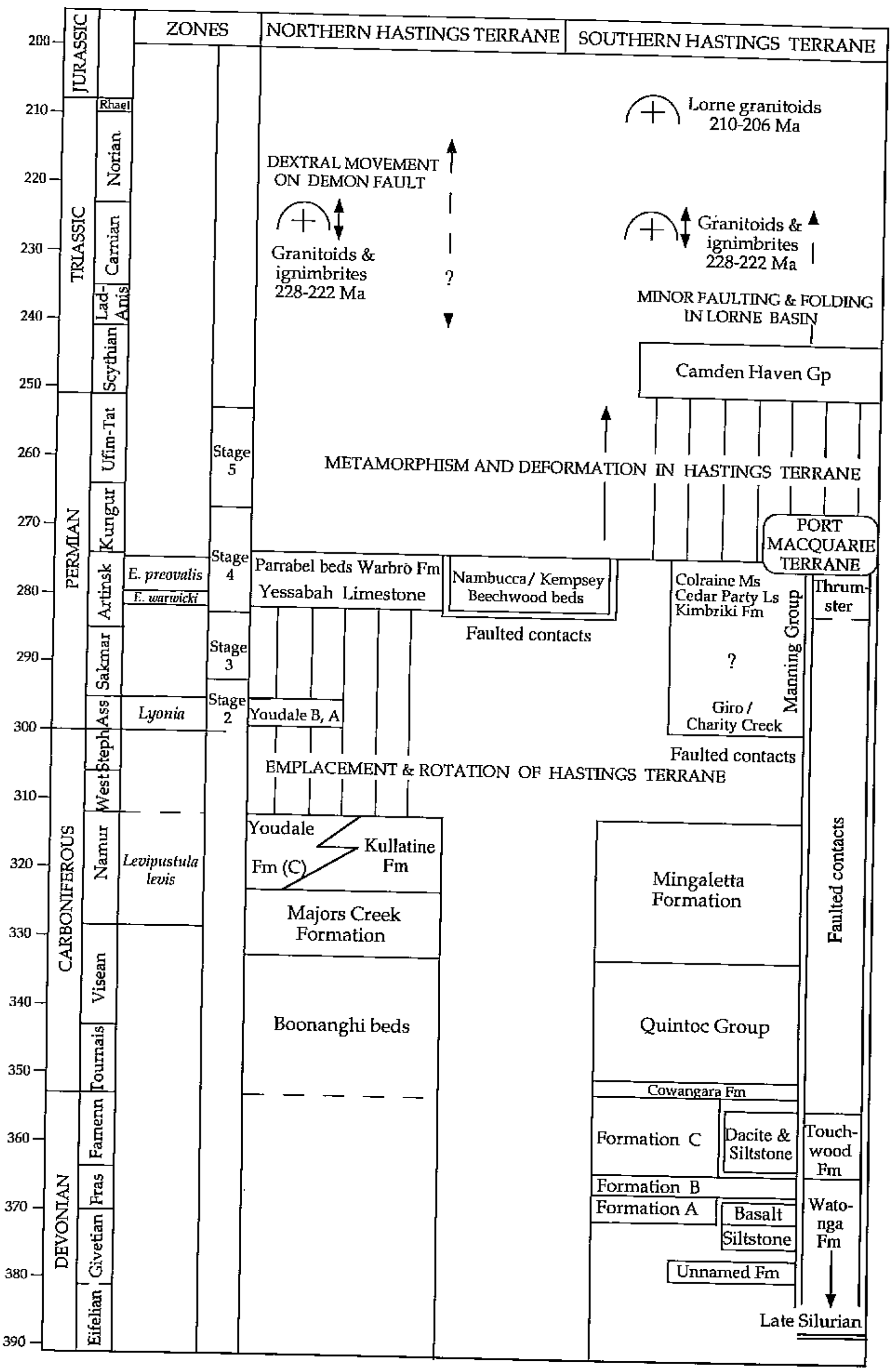

Figure 2 Time-space diagram for the Hastings Terrane (modified from Roberts *et al.* 1993a).

conformably overlying Kullatine Formation consists of predominantly red diamictite, conglomerate, lithic sandstone and siltstone, deposited or slumped into (Lindsay 1969) a relatively shallow marine environment (Lennox & Roberts 1988). The Kullatine Formation both intertongues with and underlies a finer grained succession of siltstone, graded lithic sandstone and tuff (Youdale Formation, unit C) in the western Northern Hastings Terrane. The turbiditic nature of this Carboniferous part of the Youdale Formation compared with shallow-marine traction-current deposits in the Kullatine Formation, together with evidence from the Majors Creek Formation, indicates a palaeoslope towards the west or southwestern part of the Northern Hastings Terrane (Lindsay 1969; Lennox & Roberts 1988).

Levipustula levis Zone faunas in the Majors Creek, Kullatine and Youdale (unit C) Formations indicate an age ranging from late Visean to Namurian (Roberts *et al.* 1993a). The ammonoid *Cravenoceras kullatinense* at the base of the Kullatine Formation (Campbell 1962) restricts that part of the formation to the Namurian or younger, but the age of the upper part of the formation cannot be determined because the top of the *Levipustula levis* Zone remains undated (Roberts *et al.* 1993b).

Early Permian sediments disconformably overlying the Kullatine Formation and unit C of the Youdale Formation include diamictite and siltstone (units B and A of Bourke's 1971 Youdale Formation), conglomerate, lithic sandstone and siltstone (Commong Formation), the Yessabah Limestone, mudstone, lithic sandstone and limestone of the Warbro Formation and diamictite, conglomerate, siltstone, graded lithic sandstone and minor limestone of the Parrabel beds (Roberts & Lennox 1988; Roberts *et al.* 1993a). Faults juxtapose northeastern parts of the Northern Hastings Terrane with turbiditic lithic sandstone, siltstone, diamictite and conglomerate (Kempsey beds) which are also Early Permian in age (Runnegar 1970; Figure 2).

In the Southern Hastings Terrane the oldest rocks are Middle Devonian in age (Roberts *et al.* 1993a; Figure 2) and there is a well-defined Frasnian to Carboniferous succession extending from the faulted contact with the Anaiwan Terrane in the west towards Wauchope in the east. The lower three units of this succession, recognized by Ishiga and Leitch (1988), consist of basaltic, andesitic and dacitic volcanics with siltstone and sandstone (unit A); mudstone with minor tuff and basalt (unit B); and graded sandstone and siltstone of Famennian to earliest Carboniferous age (unit C). The Cowangara Formation (Feenan 1984), or unit D of Ishiga and Leitch (1988), a turbiditic laminated siltstone and sandstone, is overlain by sediments of the Quintoc Group (Roberts *et al.* 1993a, modified from West 1990) containing units with graded sandstone, siltstone and conglomerate; siltstone; volcanogenic sandstone, siltstone, tuffs and allochthonous limestone with late Tournaisian fossils (Roberts *et al.* 1993a); and siltstone. The overlying Mingaletta Formation (revised by Roberts *et al.* 1993a after Hamilton 1982) contains both marine siltstone with *L. levis* Zone faunas and continental volcanogenic lithic sandstone, coal, rhyolite and tuff; the age of this formation is taken as late Visean to Namurian. In addition to this clearly delineated sequence, other rock units of Devonian or unknown ages are present within the Southern Hastings Terrane. One of these units, which was sampled for this study, is a basalt underlying a unit of siltstone within a fault block at Ellenborough, southeast of Yarras. The basalt is identified as probably Late Devonian in age on the basis that basaltic volcanics are known only from lower parts of the Devonian succession within the Southern Hastings Terrane.

Younger Permian sediments faulted against the Devonian to Carboniferous succession include the Beechwood beds (Brunker 1970) and the Manning Group (Voisey 1958; Leitch 1988). Both the Devonian to Carboniferous and Permian successions are disconformably overlain by Early Triassic sediments of the Camden Haven Group (Pratt & Herbert 1973) in the Lorne Basin.

Structure and tectonic history

Structurally, the Northern Hastings Terrane is characterized by a northwesterly structural grain (Figure 1c), related predominantly to the large Parrabel Dome, and three phases of folding; east–west, northwest-trending and northeast-trending. The terrane is cut by three populations of faults including: (i) northwest-trending faults with mainly sinistral strike–slip movement and evidence of later reactivation; followed by (ii) northeast-trending faults with dextral or sinistral strike–slip or dip–slip movement, with small displacement; and (iii) late meridional dip–slip faults. This contrasts with the Southern Hastings Terrane in which there is a single phase of meridional folding and three different fault populations: (i) early meridional dip–slip faults; (ii) later northeast-trending sinistral strike–slip or rare dip–slip faults; and (iii) final northwest-trending faults with both sinistral and dextral strike–slip movement (Roberts *et al.* 1993a).

Major geological and structural events affected the Hastings Terrane in the Late Carboniferous to Early Permian, the Late Permian and in the Late Triassic (Figure 2). These events must have been preceded by movement of the Hastings Terrane from a position within the fore-arc basin, possibly somewhere southeast of the Myall region, to one adjacent to an actively eroding accretionary prism, as indicated by clasts of that prism and its intruding granitoids within the Kullatine and lower Youdale (unit C) Formations. Roberts *et al.* (1993a) postulated movement of the Hastings Terrane along transcurrent faults which, according to the revised calibration of the Carboniferous and Early Permian in eastern Australia (Roberts *et al.* 1993b), would have taken place during the Namurian to possibly the Westphalian.

Uplift in the later part of the Late Carboniferous took place throughout both the Northern Hastings Terrane and Southern Hastings Terrane prior to deposition of sediments in the Early Permian (?Asselian). By the Artinskian the Northern Hastings Terrane was in juxtaposition with the Nambucca 'Trough' (Lennox & Roberts 1988; Roberts *et al.* 1993a), deposition taking place both in the trough as well as in the earlier formed successor basins over the Hastings Terrane. Sediments were to a large extent derived from the accretionary prism and intruding granitic plutons of the New England Orogen to the west.

The first major phase of folding within the Southern Hastings Terrane and Northern Hastings Terrane probably took place at slightly different times. The single phase of folding in the Southern Hastings Terrane, which has the same meridional trend as that in the Hunter-Myall region (Roberts *et al.* 1991), probably took place prior to 265–269 Ma, the time of intrusion of the Barrington Tops Granodiorite into folded strata within the Tamworth Belt (Roberts & Engel 1987; Collins *et al.* 1993). The first phase of folding in the Northern Hastings Terrane, which has the same east–west trend as axial plane cleavage in slates within the Nambucca Trough, coincided with deformation and metamorphism within that trough at 260 Ma (Fukui *et al.* 1990). Following the major deformation, basin subsidence in the Early Triassic led to the accumulation of post-orogenic quartzose and red-bed sediments (Camden Haven Group) in the Lorne Basin.

Faulting, minor folding and the emplacement of syntectonic granitoids and rhyolitic volcanism took place in the Late Triassic, the igneous events being dated at around 226 Ma (Flood *et al.* 1993; Roberts *et al.* 1993a). During this time, dextral movement on a southern extension of the Demon Fault caused refolding and faulting in the northeastern part of the Northern Hastings Terrane

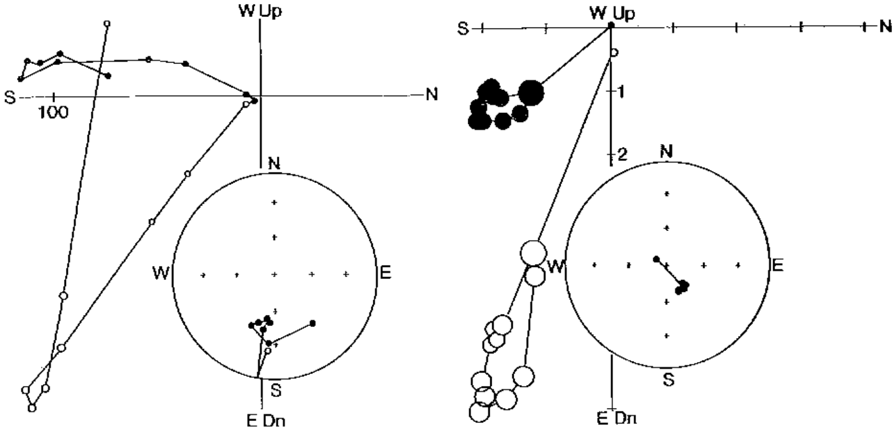

Figure 3 Basalt at Ellenborough. Orthogonal projections and equal-area stereographic overlays showing examples of the behaviour of samples observed on thermal demagnetization (steps shown are natural remanent magnetization and nominally 200° C, 300° C, 400° C, 500° C, 530° C, 550° C, 560° C, 570° C, 580° C, sometimes with extra steps between the last few steps). For the orthogonal projections, solid circles represent magnetization vectors projected onto the horizontal plane and open circles represent projections onto the vertical plane. The circle radii are 1 standard deviation from the mean vector end-points. For the stereographic overlays, solid circles refer to the lower hemisphere (reversed polarity), while open circles refer to the upper hemisphere (normal polarity). Units are mAm^{-1} ($\times 10^{-6}$ emu/cc).

and the Kempsey beds, and parts of the Lorne Basin were affected by minor folds and faults. A final episode of granitoid intrusion took place within the Lorne Basin in the Early Jurassic (Shaw *et al.* 1991).

SAMPLING

A geological sketch map showing the distribution of sampling sites is given in Figure 1. Grid co-ordinates of sites are provided in the Appendix. Initial investigations concentrated on identifying rock units which may have retained a palaeomagnetic record dating from formation, or close to this time. In a preliminary palaeomagnetic study of the Hastings Terrane by Idnurm and Scheibner (1974) to test for tectonic rotation of the block, it was suggested that if the pervasive overprinting could be avoided then the palaeomagnetic method might succeed, although they cautioned that the steep palaeo-inclinations expected from Carboniferous–Permian rocks would detract from the sensitivity of the method. Idnurm and Scheibner (1974) attributed the magnetic overprinting in the Hastings Terrane to weathering and emphasized the importance of sampling fresh material. They concluded that fresh fine-grained red-beds of the Late Carboniferous Kullatine Formation (Figure 1) were the most prospective rock type.

Apart from the Kullatine Formation, other lithologies sampled from the Northern Hastings Terrane include the Late Carboniferous Majors Creek Formation, the Early Permian Yessabah Limestone and the Late Triassic Werrikimbe Volcanics. This last formation was sampled to investigate the directions of any magnetic overprints associated with widespread Triassic igneous activity. The Werrikimbe Volcanics are the volcanic expression of granitic intrusions, some of which do not crop out but are inferred from biotite-grade thermal metamorphism (Leitch *et al.* 1982). Units sampled from the Southern Hastings Terrane include the Late Devonian (?) basalt at Ellenborough, the Early Carboniferous Taree Limestone (Quintoc Group), the Early Permian Cedar Party Limestone (Manning Group) and serpentinites associated with the southwestern margin of the block.

METHODS AND TECHNIQUES

Routine palaeomagnetic methods (McElhinny 1973; Collinson 1983) were used throughout. All samples were subjected to alternating field and thermal demagnetization. Natural remanent magnetization and laboratory-induced remanences were measured using either a Canadian Thin Film three-axis cryogenic magnetometer or an upgraded and modified fluxgate spinner magnetometer. The demagnetizers used were a Schonstedt AF demagnetizer model GSD-1 and the CSIRO three-stage carousel furnace. The furnace is housed inside a 4 m ten coil Helmholtz set with automatic feed-back maintaining zero-field (< 5 nT).

Components of magnetization have been isolated using an interactive version of LINEFIND (Kent *et al.* 1983). The linear segments are fitted to data points weighted according to the inverse of their measured variances. The variances are represented in plots of orthogonal projections by different diameter circles.

RESULTS

Many of the units sampled did not yield significant or consistent results. Those units that failed to fulfil basic palaeomagnetic reliability criteria, that is, Q< 3 (Van der Voo 1990) include the Majors Creek Formation, the Taree Limestone, the Cedar Party Limestone, the Yessabah Limestone and the serpentinite. Many of the samples collected from the limestone units (a total of 68 samples) possessed reversed components of magnetizations, although these could not be isolated with sufficient precision to warrant further analysis using either thermal

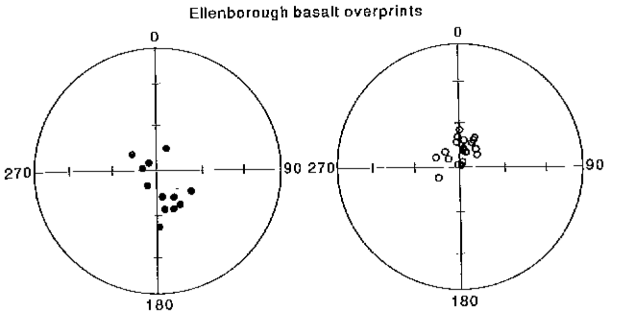

Figure 4 Basalt at Ellenborough. Stereographic projections of sample directions. Conventions as for Figure 3.

alternating field or a combination of cleaning methods. Results considered reliable are discussed in stratigraphic order, beginning with the lowest unit. Comments on the results from these sites are given in the Appendix.

Basalt at Ellenborough

Directions of natural remanent magnetization from the basalt at Ellenborough are dominantly of normal polarity, somewhat steeper in inclination than either the present field or the dipole field. The natural remanent magnetization intensities varied greatly from in excess of 3 Am^{-1} (3×10^{-3} emu/cc) to less than 10 mAm^{-1} (10^{-5} emu/cc). The higher intensities are probably associated with lightning. Although these intensities are usually associated with single component magnetizations, they are scattered in direction and soft to alternating field demagnetization.

Other samples revealed two component magnetizations (Figure 3) which were best resolved using thermal cleaning. Normal polarity components were removed by heating to 500° C to reveal components of reversed polarity. The reversed components were demagnetized by about 580° C, indicating that they were most probably carried by magnetite. The mean directions of these components are anti-parallel and are interpreted to be thermal overprints, perhaps recording a geomagnetic field reversal. The means are Dec. = 7.6°, Inc. = −79.9° (α_{95} = 8.2°) and Dec. = 170.2°, Inc. = 79.4° (α_{95} = 11.4°) yielding corresponding pole positions of Lat. = 50.7° S, Long. = 148.8° E (A_{95} = 15.4°) and Lat. = 49.4° S, Long. = 146.2° E (A_{95} = 20.4°). Directions of individual components are plotted in Figure 4 and site mean directions, overall mean directions and mean pole positions are given in Table 1. A_{95} and α_{95} are 95% confidence radii for poles and directions, respectively, following the method of Fisher (1953).

Kullatine Formation

The natural remanent magnetization intensities of the Kullatine Formation varied from about 75 mAm^{-1} (75×10^{-6} emu/cc) to about 10 mAm^{-1} (10^{-5} emu/cc). This is typical for red-beds whose remanence is predominantly carried by hematite. At most sites directions of natural remanent magnetization from the Kullatine Formation were well grouped close to, or a little steeper than, the present field direction. However, at the two sites from near Kookaburra (Kul5 and Kul6) natural remanent magnetization directions were shallow to the northwest. These were the only sites where magnetizations with well grouped shallow directions were observed. These shallow components were removed by thermal cleaning to about 500° C, or more readily by an alternating field of about 40 mT. Although these components have an unfamiliar direction (Table 2) and are relatively soft, lightning does not seem to be responsible because high intensities are absent and the two sites are widely separated (by several hundred metres). The significance of these less stable components at sites Kul5 and Kul6 is therefore obscure. However, low temperature components identified at other sites were of steep normal polarity, similar to the low temperature components found in other units (Table 2). These are interpreted to be overprint magnetizations related to uplift and cooling or metamorphism (see later discussion).

Samples from most sites possess two to three components of magnetization. For samples in which three components could be identified, anti-parallel characteristic magnetizations were resolved after removing the low

Table 1 Summary of results from the basalt at Ellenborough.

	Low Temperature				High Temperature			
Site	*n*	Dh(°)	Ih(°)	α_{95}(°)	*n*	Dh(°)	Ih(°)	α_{95}(°)
Elb1	7	18.2	−81.5	5.1	1	177.7	52.6	—
Elb2	7	11.6	−76.9	9.1	—			
Elb3	3	6.1	−77.0	17.0	2	133.3	67.3	—
Elb4	3	346.1	−73.7	10.3	2	152.6	63.6	—
Elb5	2	274.8	−80.1	—	3	267.3	87.6	40.4
Elb6	3	59.4	−72.4	18.7	4	224.2	83.4	13.0
Mean	6	7.6	−79.9	8.2	11	170.2	79.4	11.4

Low temperature pole: Lat. = 50.7° S, Long. = 148.8° E, A_{95} = 15.4°; High temperature pole: Lat. = 49.4° S, Long. = 146.2° E, A_{95} = 20.4°.

A_{95} and α_{95} follow normal usage (Fisher 1953).

Site: Lat. = 31.5° S, Long. = 152.5° E.

Dh, ih: declination and inclination with respect to present horizontal.

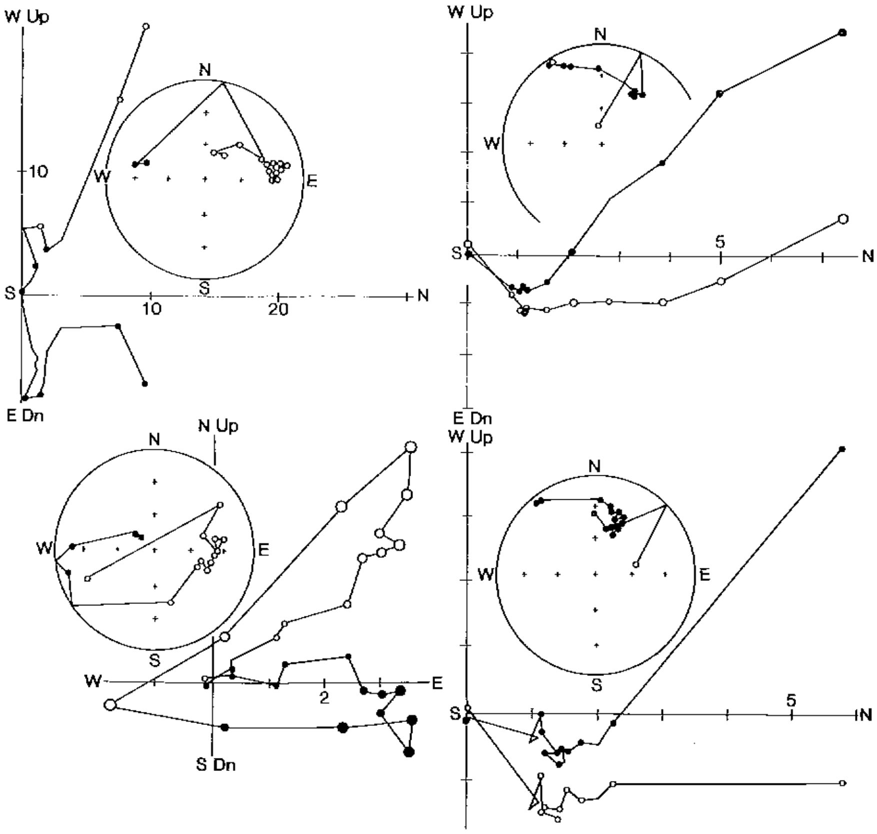

Figure 5 Kullatine Formation. Orthogonal projections and stereographic overlays showing examples of the behaviour of samples observed on thermal demagnetization (steps shown are natural remanent magnetization and nominally 150° C, 250° C, 300° C, 400° C, 450° C, 500° C, 550° C, 575° C, 600° C, 625° C, 650° C, 675° C, 685° C, 695° C, and 700° C). Note some lower temperature steps have been omitted for clarity. Conventions as for Figure 3.

temperature steep normal component. Examples of these are plotted in Figure 5 where a west and downward intermediate component succumbs to an east and upward component at high temperatures. This suggests that the red-beds acquired their characteristic magnetizations over a long period of time, and implies that secular variation has been averaged on the scale of a drill core sample. More significantly, the coexistence of both polarities is strong evidence that the magnetizations have recorded a palaeomagnetic dipole direction. Thus for sites Kul2 and Kul7 a characteristic magnetization directed upward to the east has been determined, while for sites Kul5 and Kul6 there is a characteristic component to the northeast and down. Table 2 summarizes the results from the Kullatine Formation. Directions of the low temperature and characteristic magnetizations are plotted in

Table 2 Summary of results from Kullatine Formation.

	Low Temperature				High Temperature					
Site	*n*	Dh(°)	Ih(°)	α_{95}(°)	*n*	Dh(°)	Ih(°)	Dp(°)	Ip(°)	α_{95}(°)
Kul1	10	4.4	-70.5	4.7	—	—	—	—	—	—
Kul2	13	351.1	-72.4	3.3	15	88.6	-48.5	160.5	-58.1	6.5
Kul3	6	346.6	-72.3	4.9	—	—	—	—	—	—
Kul4	6	352.3	-75.1	4.4	—	—	—	—	—	—
Kul5*	10	*326.3*	*-12.0*	3.4	11	31.5	37.9	353.2	66.4	8.0
Kul6*	8	*307.4*	*1.8*	6.7	9	28.3	35.4	353.8	62.8	11.1
Kul7	11	15.2	-77.7	6.8	7	89.7	-39.5	144.2	-56.0	14.7
Mean	5	357.1	-73.8	4.0	4	—	—	161.6	-61.4	9.4

*Italicized directions not included in calculation of the mean (see text).

Low temperature pole: Lat. = 61.0° S, Long. = 155.6° E, A_{95} = 6.9°; High temperature pole: Lat. = 14.4° N, Long. = 139.3° E, A_{95} = 13.4°.

Mean Site: Lat. = 31.1° S, Long. = 152.5° E.

A_{95} and α_{95} follow normal usage (Fisher 1953).

Plunge 10° to 308° (Lennox & Roberts 1988); Bedding (dip, dip azimuth): Kul2 and Kul7 50° to 045°; Kul5 and Kul6 40° to 240°.

Dh, Ih: declination and inclination with respect to present horizontal; Dp, Ip: declination and inclination with respect to palaeo-horizontal (plunge and bedding corrected).

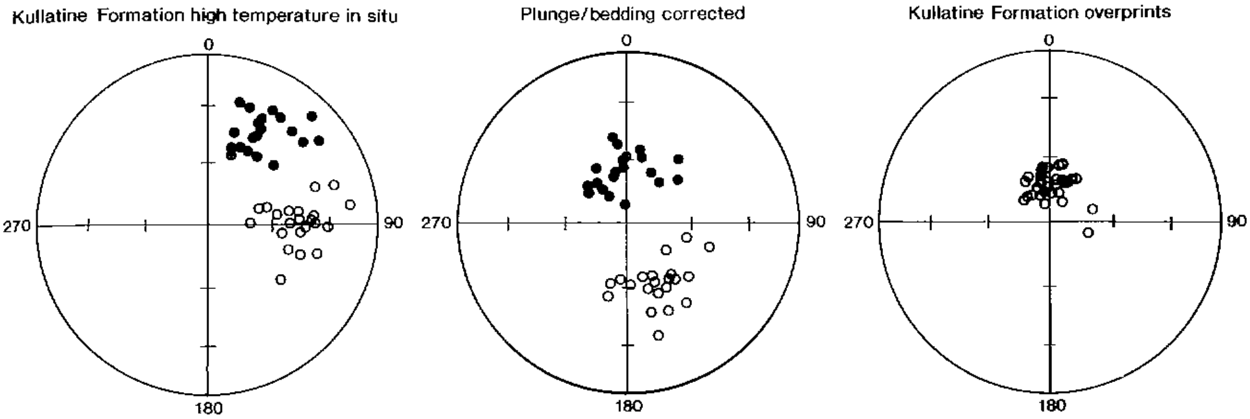

Figure 6 Kullatine Formation. Stereographic projections of sample directions. Conventions as for Figure 3.

Figure 6. Characteristics directions are shown both *in situ* and after correcting for a regional plunge of 10° to 308° (Lennox & Roberts 1988) and the appropriate bedding attitude. Clearly the directions are brought into better agreement, that is to a common magnetic axis, after structural correction. Applying a fold test (McFadden 1990) to the unplunged (although not unfolded) directions yields a test statistic, SCOS, of 3.919 (95 and 99% critical values of 2.335 and 3.180, respectively). This indicates that the offset of directions from their mean direction is well correlated with the dip direction of bedding. After complete unfolding SCOS is only 1.492 indicating no correlation in the distribution of directions and dip direction, and suggests that the strata acquired its characteristic magnetization in this attitude. The timing of the characteristic magnetization is therefore pre-folding and pre-plunging, although correcting for the latter makes a trivial difference. For the purposes of calculating characteristic site mean directions, all polarities are treated as normal for those sites in which both normal and reversed polarity magnetizations have been identified.

After correction for structure the Kullatine Formation yields a mean primary direction of Dec. = 161.6°, Inc. = −61.4° and α_{95} = 9.4°, with a mean pole position of Long. = 139.3° E, Lat. = 14.3° N and A_{95} = 13.4°. The mean low temperature direction for the Kullatine Formation, referred to here as the overprint, is Dec. = 357.1°, Inc. = −73.8° and α_{95} = 4.0°, with a mean pole position of Long. = 155.6° E, Lat. = 61.0° S and A_{95} = 6.9°.

Werrikimbe Volcanics

Intensities of natural remanent magnetization varied markedly with the composition of each flow. The intensities of the felsic types were less than 10 mAm^{-1} (10^{-5} emu/cc) while intensities of the more mafic types were up to 200 mAm^{-1} (2×10^{-4} emu/cc). The magnetization of the felsic types was more stable than the more mafic types, although in general, all the remanences were moderately to highly stable. The remanences behaved in a simple manner during both thermal or alternating field cleaning. Most samples possessed only one component while some possessed two magnetic components that were resolved during cleaning. Where developed sufficiently, the low temperature components were of normal polarity, but in all sites the characteristic component was reversed. The characteristic components were demagnetized by 580° C indicating magnetite as the probable carrier. Examples of thermal cleaning are plotted in Figure 7. Results are summarized in Table 3.

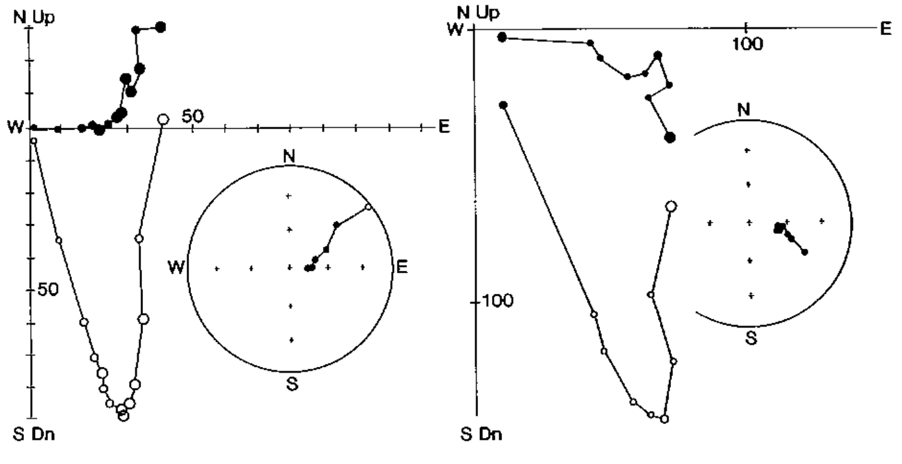

Figure 7 Werrikimbe Volcanics. Orthogonal projections and stereographic overlays showing examples of the behaviour of samples observed on thermal demagnetization (steps shown are natural remanent magnetization and nominally 200° C, 300° C, 400° C, 500° C, 530° C, 550° C, 560° C, 570° C, 580° C and 585° C, sometimes with extra steps between the last few steps). Conventions as for Figure 3.

Table 3 Summary of results from the Werrikimbe Volcanics.

Site	n	High Temperature Dh(°)	 Ih(°)	 α_{95}(°)
Wer1	6	15.7	71.3	6.7
Wer2	4	126.7	68.8	10.9
Wer3	6	72.3	67.9	5.6
Wer4	6	79.4	70.7	2.1
Wer5	11	177.4	64.2	2.9
Wer6	11	106.2	66.7	4.5
Mean	6	100.8	75.1	14.9

High temperature pole: Lat. = 31.6° S, Long. = 185.3° E, A_{95} = 26.6°.

Mean Site: Lat. = 31.3° S, Long. = 152.3° E.

A_{95} and α_{95} follow normal usage (Fisher 1953).

Dh, Ih: declination and inclination with respect to present horizontal.

Only the characteristic component was analysed because the low temperature component was encountered sporadically. Most samples had very high unblocking temperatures, indicating that they apparently contain (pseudo-) single domain magnetite which has not acquired significant secondary magnetization since initial cooling. That the characteristic magnetization dates from initial cooling is supported by the directions of each flow being significantly different (Figure 8, Table 3), apparently recording secular variation. Because a total of six flows has been sampled, and the directions show a reasonable spread, it seems likely that secular variation has been averaged fairly well. In addition, it seems unlikely that the high temperature magnetizations of these rocks have been altered since their formation.

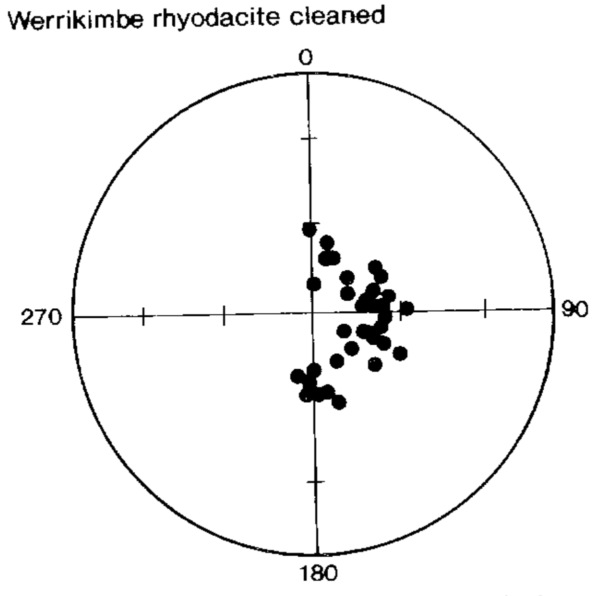

Figure 8 Werrikimbe Volcanics. Stereographic projections of sample directions. Conventions as for Figure 3.

The mean high temperature direction for the Werrikimbe Volcanics is Dec. = 100.8°, Inc. = 75.1° and α_{95} = 14.9°, with a mean pole position of Lat. = 31.6° S, Long. = 185.3° E and A_{95} = 26.6° (Table 3).

DISCUSSION

Overprint magnetizations

The magnetization of the basalt at Ellenborough and the low temperature component of magnetization of the Kullatine Formation are interpreted to be overprint

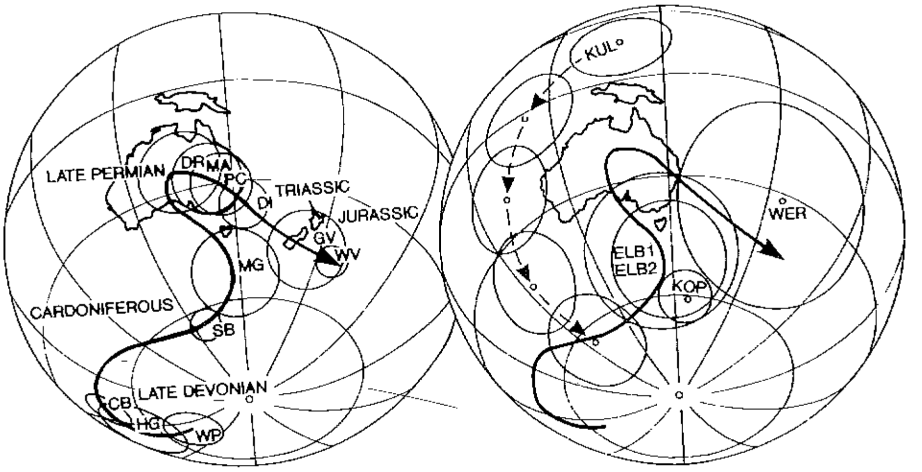

Figure 9 Left-hand equal-area projection showing Australia's Late Palaeozoic–Early Mesozoic apparent polar wander path using reliable poles from stable areas, WP: Worange Point (Thrupp *et al.* 1991), HG: Hervey Group (Li *et al.* 1988), CB: Canning Basin limestone (Hurley & Van der Voo 1987), SB: Snowy River Volcanics/Buchan Caves Limestone overprint pole (Schmidt *et al.* 1987), MG: Main Glacial Stage (Irving 1966), DR: Dundee Rhyodacite (Lackie 1988), MA: Moombi Adamellite (Lackie 1989), DI: Dundee Ignimbrite (Lackie 1988), PC: Patonga Claystone (Embleton & McDonnell 1980), WV: Western Victorian Basalt (Schmidt 1976a), GV: Garrawilla Volcanics (Schmidt 1976b). Right-hand equal-area projection showing poles from this paper superimposed on the apparent polar wandering path. The pole labelled KUL is from the pre-deformation magnetizations of the Kullatine Formation, KOP is from the overprint magnetizations of the Kullatine Formation, and ELB1 and 2 are from the low and high-temperature components of the basalt at Ellenborough. Note that KUL is shown before, during and after a notional 130° rotation of the Hastings Terrane.

netizations. Pole positions from these are plotted in
re 9 as ELB1 for the low temperature component
the basalt at Ellenborough, ELB2 for the high
perature component from the same basalt, and KOP
he overprint found in the Kullatine Formation. The
obvious cause of remagnetization in the Hastings
ane is the high heat flow associated with the Late
sic magmatism (Leitch *et al.* 1982), yet the overprint
positions appear to be distinct from all known
sic pole positions, including that of the Late Triassic
rikimbe Volcanics (Figure 9). An alternative mechan-
is therefore required to explain the overprinting.
arly Permian remagnetizations are pervasive else-
e in the New England Orogen (Klootwijk & Giddings
; Schmidt & Lackie 1993). The similarity of the
print pole positions determined here, with other
print poles, for example, that of the Seaham
nation (Main Glacial Stage of Irving 1966) in the
ter Valley 160 km to the south, suggests that they
be related to the same remagnetization event.
vever, it is well established that during the Late
boniferous and Permian, the geomagnetic polarity
predominantly reversed. This period is known as
Late Palaeozoic Reversed Superchron, formerly the
man Interval (Irving & Parry 1963), and the
netization of the Seaham Formation and other
printed units are indeed reversed. While the pole
tions from the overprints found in the basalt at
nborough and the Kullatine Formation are close to
of the Seaham Formation, the polarity of the
netizations are mixed, and predominantly normal.
would appear to disqualify the Late Palaeozoic event
being a possible cause of the overprinting although,
eported by Irving and Pullaiah (1976, figure 12) and
rill and McElhinny (1983, p. 154), there are several
es of normal polarity within this reversed interval.
articular, these normal zones cluster around the Early
mian and therefore the possibility that the basalt at
nborough and the Kullatine Formation may have
remagnetized around that time cannot be unequivo-
y excluded.

he only other segment of the apparent polar wander-
path that is both younger than the rock units and
mbles the overprint poles corresponds to the mid-
taceous. Schmidt and Embleton (1981) have identified
rprinting of this age from the Sydney Basin, and
ted the overprinting to high heat flow, accompanied
uplift and cooling, during early stages of rifting in
Tasman Sea. Overprints identified with these events
of normal polarity, corresponding with the Cretaceous
rmal Superchron (Merrill & McElhinny 1983, p. 154),
le those found here are of mixed polarity, as discussed
ve. It is conceivable that rifting occurred at slightly
erent times along the New South Wales margin,
nitting the possibility of mixed polarities. Therefore,
le there is no geological evidence for a mid-Cretaceous
rmal event in the Hastings Terrane, such as the high
inite reflectance values in the Sydney Basin (Middleton
Schmidt 1982), the possibility of mid-Cretaceous
rprinting cannot be discounted.

t is suggested here that orogenic or pre-rifting pro- for the pervasive magnetic overprinting encountered by Idnurm and Scheibner (1974). In conclusion, having ruled out Late Triassic overprinting, we are unable to correlate the overprinting with either of the remaining contenders, the Early Permian orogenic activity or the Cretaceous initial rifting. The timing and cause of the remagnetization remain unclear. Further palaeomagnetic work should be done on the biotite grade hornfels in the Northern Hastings Terrane to provide a better pole position for the magmatism to compare with those from this study.

Characteristic magnetizations

The pole position from the Late Triassic Werrikimbe Volcanics is not significantly different from other Triassic/Jurassic units (Figure 9) although it is not well defined ($A_{95} = 27°$). Since the Werrikimbe Volcanics appear to be unaltered, the characteristic remanence is thought to be original and dating from initial cooling. This is supported by the moderate amount of secular variation apparent between different flow units giving rise to a large cone of confidence. Nevertheless, the pole position from the Werrikimbe Volcanics appears to agree with poles of comparable age from elsewhere in Australia.

While the characteristic magnetization of the Kullatine Formation pre-dates deformation, the pole position is unlike any other published pole position for Phanerozoic rocks from Australia. The Kullatine pole position may be reconciled with the apparent polar wandering path if the Hastings Terrane has been rotated through 130° clockwise. Figure 9 shows the pole position rotated 130° back into its putative original position. An anti-clockwise rotation of Hastings Terrane of about 230° also satisfies the data, since this would also bring the Kullatine Formation pole into agreement with the Carboniferous segment of the apparent polar wandering path, in accordance with the age of these rocks (Figure 10). Because of the uncertainties in determining the pole position (13°, Table 2), both in stratigraphic position and in the apparent polar wandering path calibration, it is not possible to establish a precise palaeo-position for the Hastings Terrane. While these data are insensitive to translational displacements, a clockwise rotation of the Hastings Terrane is not compatible with models produced by either Cawood (1982) or Korsch and Harrington (1987). Although an anti-clockwise rotation is in the same sense as these models, the magnitude of 230° appears to be too great by about 100°. For instance, although Korsch and Harrington (1987) do not stipulate the amount of rotation, their figures 2 and 3 suggest that an anti-clockwise rotation of between 100° to 140° is prescribed by their 'Manning Orocline'. Nevertheless, the palaeomagnetically determined rotation brings the palaeoslopes of the Tamworth Belt, facing east, and the Northern Hastings Terrane, facing west before rotation and facing southeast after rotation, into better alignment (Figure 10). Samples from the Southern Hastings Terrane proved poor palaeomagnetic recorders, either completely overprinted

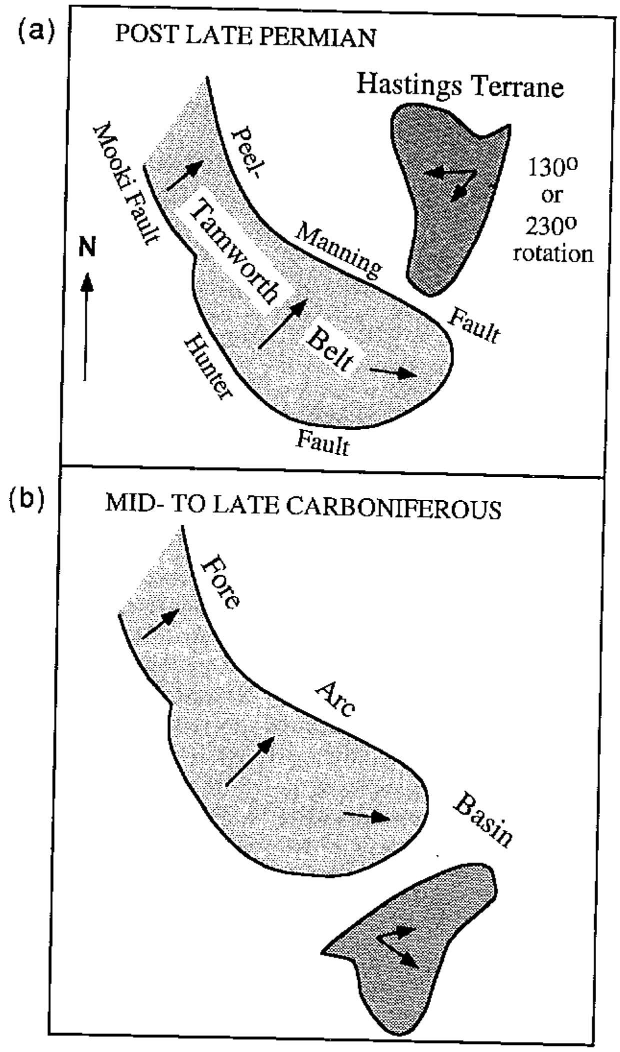

Figure 10 Cartoon indicating (a) the present position and (b) a possible past position for the Hastings Terrane, and the effect of rotation on the palaeoslope (arrows) of the Northern Hastings Terrane relative to that of the Tamworth Belt.

CONCLUSIONS

The overprint magnetizations and associated palaeomagnetic pole positions identified from the Kullatine Formation and the basalt at Ellenborough appear to be either Early Permian or Cretaceous. The nature of the overprinting mechanism is unclear although the most obvious candidate, the Late Triassic igneous event, is discounted on the basis of the apparent polar wandering path. Alternatives are the pervasive Early Permian remagnetization found elsewhere in New England or the initial rifting during the mid-Cretaceous.

Evidence for clockwise rotation of at least the northern part of the Hasting Terrane has been found from the palaeomagnetic investigation of several rock units. While pre-folding magnetizations were identified from the Kullatine Formation, the palaeomagnetic pole position requires 130° correction to bring it onto the Australian apparent polar wandering path. The rotation of 130° restores the facing direction of the Hastings Terrane to a southeasterly aspect, more in line with the easterly facing Tamworth Belt (Figure 10). Lack of reliable palaeomagnetic data and overprinting in the Southern Hastings Terrane prevent any interpretation of the orientation and possible rotational history of that part of the Hastings Terrane.

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APPENDIX: DETAILS OF SAMPLING SITES

Site	Grid co-ordinates*		Field no.	Comments†
Basalt at Ellenborough				
Elb1	483176	Cowa	HB11	Mostly normal, one reversed.
Elb2	484177	Cowa	HB12	All normal.
Elb3	485177	Cowa	HB13	Mostly normal, two reversed.
Elb4	486177	Cowa	HB14	Mostly normal, two reversed.
Elb5	481174	Cowa	HB32	N and R equal.
Elb6	481175	Cowa	HB33	N and R equal.
Kullatine Formation				
Kul1	694646	Kemp	HAA	Only overprint resolved.
Kul2	620692	Kemp	HAG	Multi-components, o/p+N+R.
Kul3	696640	Kemp	HB7	Only overprint resolved.
Kul4	699639	Kemp	HB19	Only overprint resolved.
Kul5	309639	Cowa	HB23	Reversed.
Kul6	303642	Cowa	HB50	Reversed.
Kul7	622693	Kemp	HB51	Normal.
Werrikimbe Volcanics				
Wer1	362597	Cowa	HB24	Felsic, weak, reversed.
Wer2	352430	Cowa	HB27	Reversed.
Wer3	353438	Cowa	HB28	More mafic, stronger, reversed.
Wer4	363451	Cowa	HB29	Reversed.
Wer5	341414	Cowa	HB53	Felsic, weak, reversed.
Wer6	349420	Cowa	HB54	More mafic, stronger, reversed.

*Kemp, Kempsey 1:100 000; Cowa–Cowarral 1:100 000.

†o/p, overprint; N, normal polarity; R, reversed polarity.